Magnetic-field-stabilized electron-hole liquid in InSb

N. A. Kalugina and É. M. Skok

Institute of the Physics of Semiconductors, Siberian Branch of the USSR Academy of Sciences

(Submitted 14 July 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **38**, No. 5, 251–253 (10 September 1983)

The frequency of stimulated photoluminescence of indium antimonide is observed to change in a jump-like manner when the magnetic field reaches a critical value. This phenomenon, which depends on the excitation intensity, is interpreted in terms of a model of condensation of an exciton gas in the liquid in the presence of a magnetic field.

PACS numbers: 71.35. + z, 78.20.Ls, 78.45. + h, 78.55.Ds

It is shown in theoretical paper[1-3] that in a sufficiently strong magnetic field H, when the cyclotron energy $\hbar\omega_c$ greatly exceeds the effective Rydberg, the motion of electrons is largely one-dimensional and the electron-hole plasma is strongly compressed by the combined action of the magnetic field and Coulomb forces. In this case, the total energy per pair of plasma particles, as a function of the electron-hole pair density, has a minimum E_m and its absolute magnitude can exceed the binding energy of the exciton ϵ_B. The minimum density at which such a situation is realized must satisfy the condition[2]

$$1 \ll p_F a_B/\hbar \ll (n a_B^3)^{1/4}\ , \tag{1}$$

where $p_F = 2\pi^2\lambda^2\hbar n$ is the Fermi momentum, a_B is the effective Bohr radius, $\lambda = (c\hbar/eH)^{1/2}$ is the magnetic length, and n is the carrier density.

Condition (1) can be realized quite simply in indium antimonide due to the low effective mass of electrons. Assuming the reduced mass of the exciton to be $\mu = m_e m_h/(m_e + m_h) = 0.013 m_0$ (m_0 is the free electron mass) and the dielectric constant to be $\epsilon = 16.8$, we obtain $a_B = 6.8\times10^{-6}$ cm, $\lambda^2 = 6.5\times10^{-8}/H$ cm^2, and $p_F = 1.3\times10^{-33}\ n/H$ erg·s/cm. For these values, both parts of the inequalities (1) are satisfied, for example, for $n\sim1\times10^{15}$, beginning with fields $H\sim10^4$ Oe. The conditions for a strong magnetic field $\hbar\omega_c \gg \epsilon_B$ and for the superquantum limit are also satisfied.

By virtue of the rectilinearity of the bands of indium antimonide, the necessity of obtaining high electron-hole pair densities creates a particular difficulty. However, the required nonequilibrium carrier density can be obtained by using intense laser radiation for pumping with a wavelength close to the width of the forbidden band of indium antimonide.

We used a nitrogen-cooled CO laser with discretely tunable wavelength in the range 5.10–5.20 μm to excite the electron-hole pairs. The intensity of the radiation incident on the specimen exceeded 1 W in the single-mode regime. A monochromatic beam was focused on the specimen in a spot with a diameter of the order of 200 μm. The n-InSb specimens ($n = 1.4\times10^{14}$ cm^{-3}, $U = 2.4\times10^5$ cm^2/V·s at 77 K) consisted of plane-parallel plates with a thickness of 500 μm. The surfaces were polished by a

0021-3640/83/170297-04$01.00

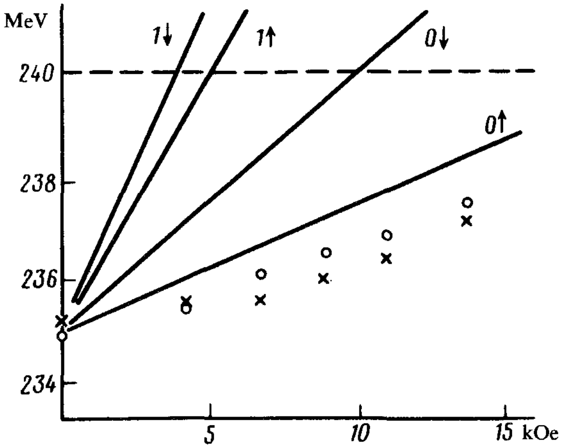

FIG. 1. Landau levels in the conduction band of InSb and the position of the peaks of stimulated emission for two levels of pumping intensity ● — Low excitation intensity; + — High intensity; $T=5$ K: the effective g factor is 50; the dashed line shows the excitation energy.

chemical-mechanical method and then etched in order to obtain a minimum surface density of states of the order of 10^{11} cm^{-2}. The specimen was attached in a vacuum to the end of a liquid helium cooled holder $T\sim 5$ K and placed between the poles of an electromagnet. The photoluminescence could be measured both from the side of the excitation and from the opposite side in transillumination geometry.

Since the angle of incidence of the pumping beam in the transillumination geometry is close to 90°, high power penetrates into the specimen and the conditions required for the appearance of stimulated radiation are easily realized. The transition from spontaneous to stimulated emission has a threshold nature, and the value of the threshold intensity depends on the magnitude of the magnetic field and decreases with increasing field.

In the absence of a magnetic field, luminescence is observed near 235 meV and is slightly displaced toward short wavelengths with increasing pumping intensity. The magnetic field leads to a sharp narrowing of the luminescence line and an increase in it intensity. With weak pumping (but, still above threshold for stimulated emission), the dependence of the maximum of the emission line on the magnetic field is nearly quadratic (Fig. 1, circles). An increase in the excitation intensity causes in the region 7–8 kOe a jump-like displacement of the emission line by approximately 0.5 meV toward long wavelengths (Fig. 1, cross marks). Generation in the same fields is unstable and depends strongly on the pumping intensity. Fluctuations in the power of the exciting laser cause the jump in the emission line. In high fields, generation occurs strictly at a single frequency over a rather broad range of intensities, beginning with some threshold value. Figure 2 is an example of generation lines in a 11.6-kOe magnetic field for two pumping intensities, a low intensity and a maximum attainable intensity in our experiment, $\sim 10^{23}$–10^{24} kV/cm^2 s. We note that with some detuning a single-mode generation regime arises and, in this case, the intermode separation in fields of 11–12

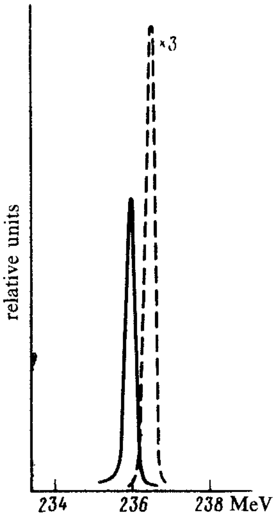

FIG. 2. Position of the stimulated emission spectra for two levels of pumping in an 11.6-kOe field. The solid curve represents a high-level excitation and the dashed curve denotes a low-level excitation.

kOe amounts to ~0.15 meV. Therefore, the displacement in Fig. 2 cannot be explained by the resonator modes.

We interpret the results shown in Figs. 1 and 2 as follows. Since the possibility of observing excitons, including diamagnetic excitons, in the absorption and photoluminescence spectra of InSb may be assumed to be well established,[4,5] it is logical to attribute the behavior of the luminescence curve in fields up to ~7 kOe to emission either of a free exciton or an exciton of the impurity complex. The quadratic dependence of the radiation frequency on the magnetic field in the region of low fields supports this assertion. In the region 7–8 kOe, according to estimates, conditions (1) can be realized and we observe a gas-liquid transition. Because of the low intensity of electron-hole pair generation in these fields, the state of the system is not yet stable enough and the ± 5% fluctuations in the power of the CO laser cause generation to jump from one frequency to another. In high magnetic fields (Fig. 2), the pumping power is sufficient to stabilize the electron-hole liquid. In fields exceeding 8 kOe, the break in generation of the long-wavelength line occurs at a lower pumping intensity. As is evident from Fig. 1, the energy per pair of plasma particles is ~1.4 meV. This slightly lower than the estimates in Ref. 2.

In conclusion, we note that an investigation of the behavior of spontaneous luminescence in the presence of magnetic and electric fields under experimental conditions close to ours led Kavetskaya *et al.*[6] to the conclusion that an electron-hole liquid, stabilized by a magnetic field, can be manifested in the luminescence spectra.

We thank L. I. Magarill for very helpful discussions and A. O. Suslyakov for help in making a CO laser.

[1] L. V. Keldysh and T. A. Onishchenko, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 70 (1976) [JETP Lett. **24**, 59 (1976)].
[2] E. A. Andryushin, V. S. Babichenko, L. V. Keldysh, T. A. Onishchenko, and A. P. Silin, Pis'ma Zh. Eksp.

Teor. Fiz. **245**, 210 (1976) [JETP Lett. **24**, 185 (1976)].
[3] T. A. Onishchenko, Élektronno-dyrochnaya zhidkost' v sverkhsil'nom magnitnom pole (Electron-Hole Liquid in a Superstrong Magnetic Field), Nauka, Moscow, 1980, Trudy FIAN Vol. 123, 7, 1980.
[4] L. M. Kanskaya, S. I. Kokhanovskiĭ, and R. P. Seĭsyan, Fiz. Tekh. Poluprovodn. **13**, 2424 (1979) [Sov. Phys. Semicond. **13**, 1420 (1979)].
[5] V. I. Ivanov-Omskiĭ, S. I. Kokhanovskiĭ, R. P. Seĭsyan, V. A. Smirnov, and Sh. U. Yuldashev, Fiz. Tekh. Poluprovodn. **17**, 532 (1983) [Sov. Phys. Semicond. **17**, 334 (1983)].
[6] I. V. Kavetskaya, Ya. Ya. Kost', N. N. Sibel'din, and V. A. Tsvetkov, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 254 (1982) [JETP Lett. **36**, 311 (1982)].

Translated by M. E. Alferieff
Edited by S. J. Amoretty